Simulating Physical Effort in Virtual Reality using Elastic Bands Wrapped around the limbs

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***Abstract*—In this report, we present a serie of simulations exploiting elastic bands wrapped around the arms or legs. We aim to evaluate the impact of haptic feedback to enhance the sensations of movement and effort in virtual reality of both passive and active users in several situations by simulating muscular contraction. To this purpose, we conceived a prototype of haptic feedback, consisting in an elastic band compressing the arms or legs to mimic muscular activity. The device only requires one servo motor and is controlled via an Arduino micro board. To evaluate the impact of these interfaces on the perception of users, we created a walking simulation, as well as a weight lifting simulation.**

I. INTRODUCTION

The realism of Virtual Reality simulation is often limited by the lack of effort feedback received by the user. One example of this, is that Virtual Reality alone can't provide a realistic weight sensation of lifting virtual objects. To answer this issue, multiple approaches have been explored. Several existing works are introducing haptic feedback to simulate weight, such as Grabity [1], which uses skin deformation to simulate tengential forces like gravity and inertia, and Shifty [2], a haptic feedback that changes its internal weight distribution to modify its moment of inertia, thus enhancing the perception of weight. Some other works focus more on the sensation of effort. For instance, The CUFF [3] uses a strip clenched around the arm to provide efforts feedback from an artificial hand controlled by the user.

The haptic feedback we propose to use also aims to provide effort feedback, but focuses on applying normal forces on the limbs, to simulate muscular contraction. This means that it only requires one motor, making the design easy to reproduce, and allowing to control multiple devices at the same time with very few components.

Wearable haptic feedback can have multiple medical applications, such as rehabilitation or compensating for the loss of sensory feedback, as presented for instance in [4]. Having a design easy to replicate and to operate is then also a high priority in order to make it available to many.

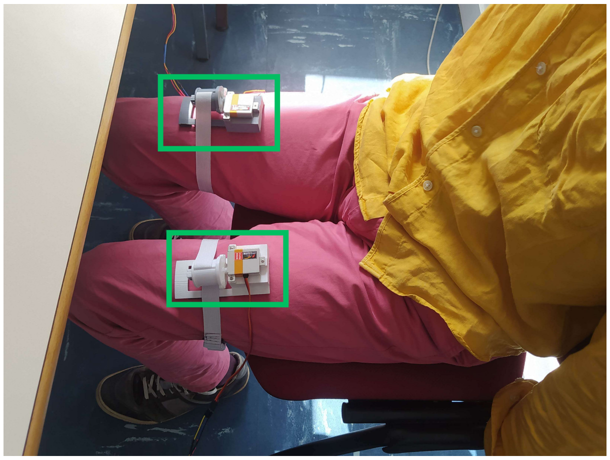


Fig. 1: Photography of two prototypes on the legs of the user. The interfaces are in green boxes.

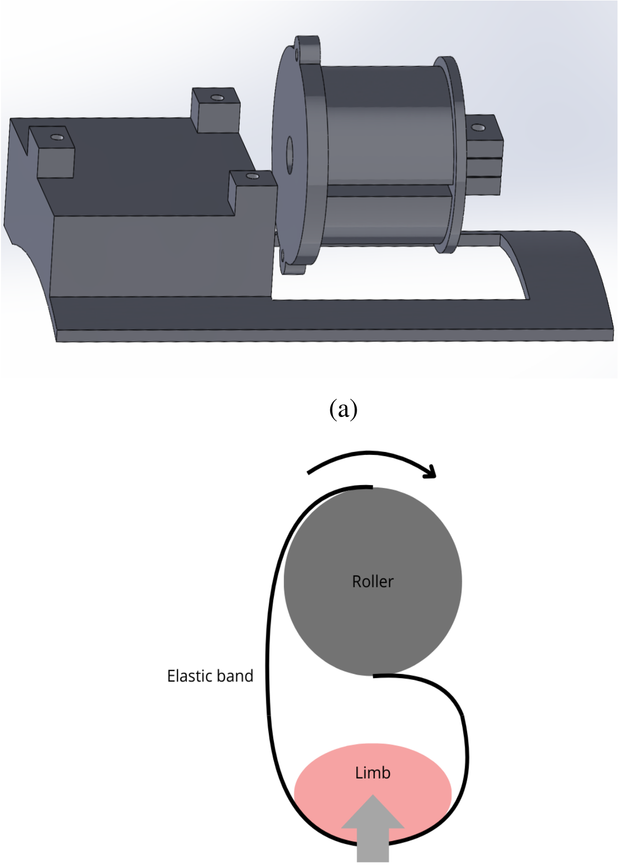
In section II-A, we will introduce the prototype of haptic feedback that will be used for future user experiments, followed by some experimental results on the elastic band of this device in section II-B. Finally, sections III-A and III-B present the two simulations developped for this project, respectively a walking simulation and a weight lifting simulation.

II. HAPTIC DEVICE

A. Description

The haptic device is a wearable interface that simulates muscle activation. It is important to have wearable devices, to make their placement modular and so, actuate both arms and legs. As a result, we aimed for a light and simple design ($\approx$ 71g). The prototype created for this project takes a form similar to the compression belt used in [5] and to the CUFF [3]. It consists of an elastic band wrapped by a motor around the arm or leg, but unlike the previously mentionned systems, it doesn't require any velcro bands to attach to the user's limb, making the installation easier. Contrary to the CUFF, this prototype is also meant to be used in Virtual Reality.

Figure 1 presents an example of utilisation of this prototype on the legs of the user.



(a)

(b)

Fig. 2: Design of the prototype (a), and device actuation principle (b) : the roller wraps the elastic band around the limb and thus, compresses it.

Figure 2a presents a montage of the prototype. It uses an elastic band to provide force feedback to the user. The caracteristics of the used elastic band are more detailed in section II-B.

Figure 2b show the actuation principle of the motor : the elastic band is wrapped around the roller part of the prototype, creating a normal pressure to the limbs of the user.

Fig. 3: Elastic band testing setup

The extension of the elastic band is given by the following formula :

$$\Delta \ell = 2 \times r \times \Delta \theta$$

where r is the radius of the roller, $\Delta \ell$ is the extension of the elastic band, and $\Delta \theta$ is the difference between the initial angle of the motor and the current angle.

The motor used is a servo motor FT3325M (Input voltage 4V-8.4V, torque 5.85 kg.cm at 4.8V), which can rotate 180°. The roller is 20 mm long, and has a radius of 14 mm, meaning that the maximum displacement of the band is around 88 mm.

B. Caracterisation of the elastic band

In order to have a model of the strip used in the prototype, we made an experiment to measure the elongation of a 20cm strip depending on the force it is subject to.

Figure 3 presents the setup used for the experiment : We used 20 cm elastic bands maintained using a vice. We then progressively added weights at the bottom of the elastic band, and measured its elongation. Figure 4 presents a graph of the relative elongation as a function of the weight attached to the band.

We used 6 different samples of length 20 cm, including a witness sample where we started with the maximum amount of weight and decreased it to make sure the order in which we measured the different elongations didn't have any significant impact.

Figure 4 presents the collected results, which are not showing a linear behaviour. However, a polynomial function of degree 2 fits quite well our experimental results. The gray dotted lines are the best fitting polynomials for each samples, and the blue full line is the best polynomial for all samples combined. The results were consistants between different samples.

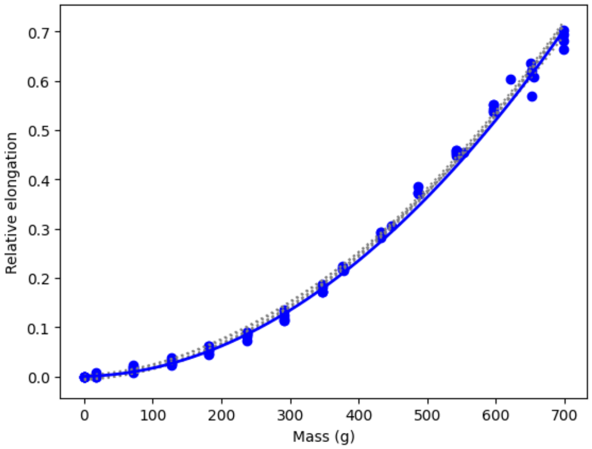


Fig. 4: Experimental results of relative elongation depending on the mass of the weights suspended to the strip. The polynomial regressions for each sample are the dotted gray line, and the polynomial regression for all measures combined is the blue full line

The best polynomial regression of degree 2 for our results is the following :

$$\Delta\tilde{\ell} = 1.3295{\times}10^{-6}m^2{+}9.1778{\times}10^{-5}m{-}3.2748{\times}10^{-3}$$

Where $\Delta\tilde{\ell}$ is the relative elongation of the strip, and m is the mass attached to the strip (adjusted R squared of 0.9959).

Further experimentations should be done to see if we can consider that the forces applied to the limbs with our prototype is proportionnal to the tangential force applied to the strip. It would also be usefull to test what forces are applied when the prototype is attached to the limbs of the user, as the band itself is responsible for attaching the prototype to the body.

III. SIMULATIONS

In this section, we will present the two simulations that were created to test the impact of the prototype on the perception of effort.

Both simulations were created using the game engine Unity (editor version 2022.3.10f1, Unity Technologies), and the avatars used were created using the open-source software MakeHuman [1]. Both scenes also have a male and female avatar available, in order to increase the sense of embodiement (presented in [6]) for the user. Section III-A presents a simple walking scene. Section III-B presents an other scene, in which the avatar lifts a weight.

Fig. 5: Virtual scene for the walking simulation, third person view

A. Walking Simulation

In this first scene, the avatar walks on an infinite straight road. This scene is relatively similar to the one used in [7] in terms of movement, but differs by the type of haptic feedback provided, which are detailed in section III-A2.

The user is sitting on a chair, experimenting passively a virtual walk while not moving. The goal of the simulation, and the experiment in which it will be used, is to measure whether or not the haptic device improves the sensation of effort during a virtual walk. As a result, we intend to compare participants' sensation of walking in different conditions : with and without haptic feedback.

1) scene components: This scene includes an avatar, which can be selected to be either male or female to match the user, walking on an infinite concrete road. Several elements, for instance bushes, road lines and poles, allow the user to easily understand that the avatar is walking. Figure 5 presents a third person view of the scene. The simulation camera is placed in place of the head of the participant, who has a first person point of view. The camera rotates according to the movement of the head of the user, but only follows the head of the avatar along the horizontal axis of the road. The vertical and lateral translations of the camera following the avatar's head were removed because they were causing cybersickness. Furthermore, a litterature review [8] recommands not adding viewpoint oscillations when embodying a first person avatar.

We used a walking animation from *Mixamo* [2] for the avatars.

2) Haptic feedback: On this scene, haptic feedback are placed on the right and left thighs of the user (just like in Figure 1) to add a sensation of effort during

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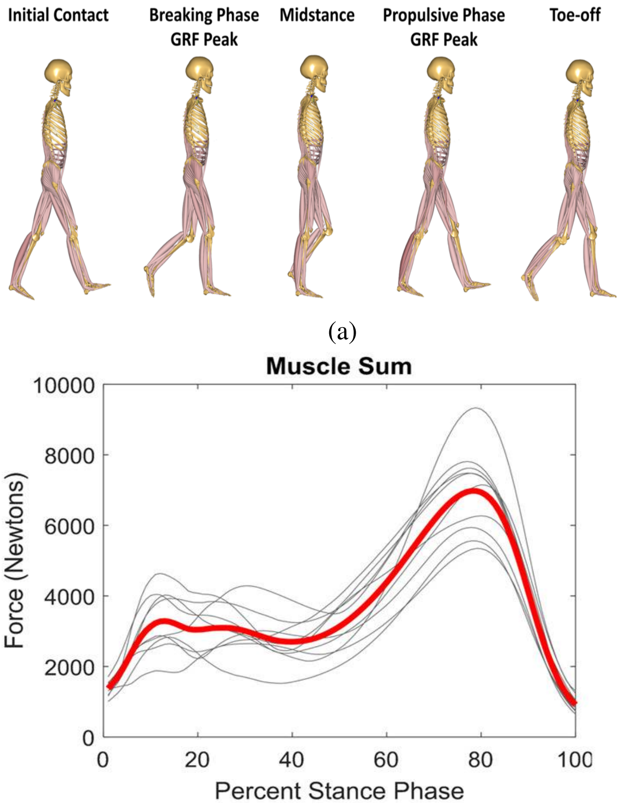
[1] https://static.makehumancommunity.org/

[2] www.mixamo.com/

the walk. The left and right motors are controlled independently. To decide when to provide haptic feedback, we used the sum of fonctionnal muscle groups forces during the walking stance presented in [9] (see Figure 6). For each leg, the corresponding motor squeezes the elastic band from 60% to 90% of the walking stance, corresponding to the propulsive phase, which is the peak of forces exerted by the muscles involved in the walking motion.



(a)

(b)

Fig. 6: Graphics extracted from [9]. (a) presents Gait events in the stance phase of the right leg. The highest ground reaction force (GRF) occurs during the breaking and propulsive phases. (b) shows the sum of functional group muscle force profiles during walking stance phase. Grey lines are average curve for each participant (six to ten stance phases per participant). Red lines are average of the ten participant average curves.

Since the main goal is to improve realism by giving an effort feedback, and not differentiate multiple effort intensities, the commands sent to the motor are only to squeeze and unsqueeze at the maximum the motor can.

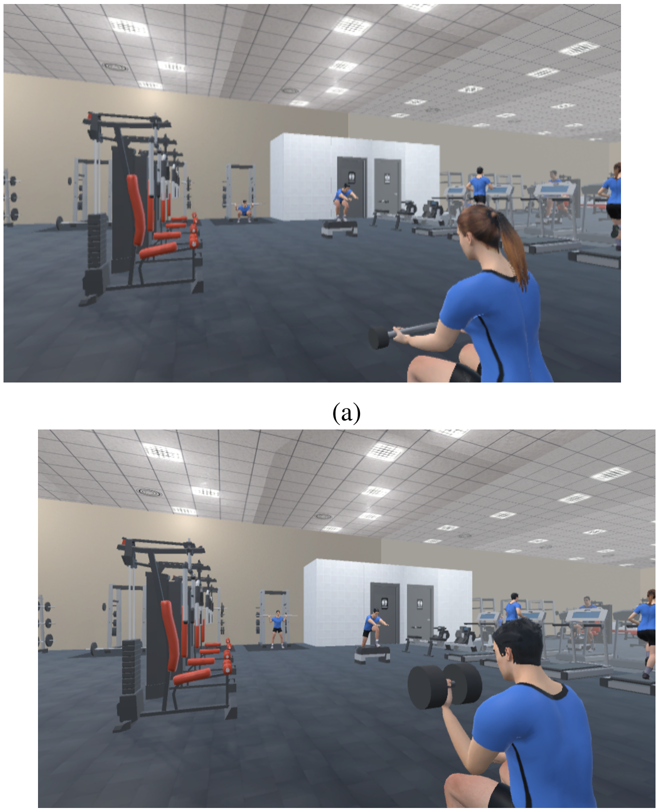
In the future, this could be changed to incorporate different levels of efforts, for instance if we add different slopes or terrains in the simulation.

B. Weight lifting simulation

In this simulation, the goal is to determine if our haptic device can enhance the sensation of effort compared to the simulation without haptic feedback, and allow to discriminate between different virtual weights.

1) Scene components: This second scene takes place in a gym, with several machines and weights to make the environment more realistic. Other avatars visible in the scene are using animations from *Mixamo*, and aim to provide a more complete gym environment.

A view of the virtual scene is presented in Figure 7.



(a)

(b)

Fig. 7: Virtual scene with a female avatar moving a small weight with both arms (a), and the same scene with a male avatar moving a bigger weigth with the left arm (b), seen in third person view

For this simulation, we used a sitting animation, again from *Mixamo*, and controlled the angle of the elbow of the main avatar via a script.

The forearm of the avatar rotates along an horizontal axis.

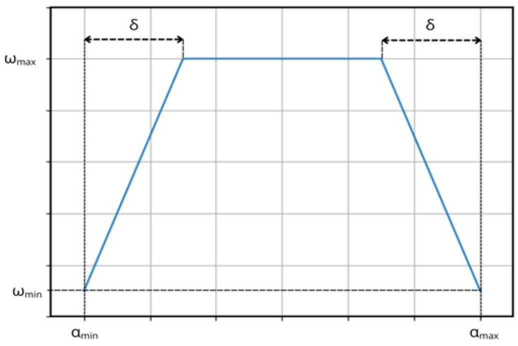
In this simulation, we can once again choose between a male or female characters, but there are several other elements of customization.

In order to test both dominant and non-dominant arms of the participants, we can move a weight with either only left or right arm (7b). Another parametrization of the scene leads to avatars lifting a weight using both arms.

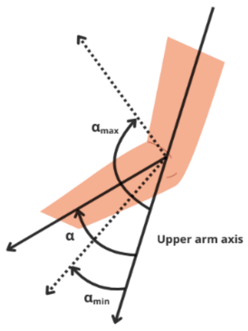
The apparent size of the weight can also be changed. This feature is added to compare the sensation of effort for different weights.

There are also two main ways to move the arm : one where the elbow rotates automatically to lift the weight (detailed in section III-B2), and one where the rotation follows a tracker in the hand of the user (detailed in section III-B3).

2) Automatic arm rotation: In this mode, the rotation of the arm is determined using a trapezoid for the rotationnal speed of the arm for a smooth and relatively realistic movement. For this configuration, the users are observing the scene passively, without moving their arms themselves.



(a) Angular speed of the arm (ω) depending on the angle of the arm (α)



(b)

Fig. 8

We note as α the angle between the direction of the upperarm and the lower arm.

We can decide as parameters of the simulation the angular range of the arm ,determined by α_{min} and α_{max}, the top speed and minimum speed of the arm ω_{max} and ω_{min}, and the angular span of the acceleration of the arm δ.

Figure 8 presents a drawing of the situation, and a graph of the speed of the arm (in absolute value), depending on the angle of the arm.

We can also scale down the speed when the arm is moving up, and depending on the mass of the weights by modifying the simulation parameters.

3) Arm rotation following a tracker: In this configuration, the user is actively moving his own arm, with a tracker in his hand. The position of this tracker is used do determine the angle of the arm to make the virtual hand follow the real one.

In order to do this, we want to compute the angle between the upperarm axis and the vector from the elbow to the hand. Since the elbow and the upperarm are not tracked, we use the avatar's elbow and upperarm. Moreover, the user's arm won't be exactly aligned with the corresponding avatar's position. We thus project the position of the hand, given by the tracker, on the plane in which the avatar's lower arm is rotating, and use this projected position to compute the angle of the lower arm applied to the avatar.

Using this method instead of directly using the orientation of the tracker for instance, helps to limit the error induced by a misalignment of the user.

For each of these configurations, we will evaluate the influence of the compressive haptic feedback on the sensation of effort in a setup where the user is using his dominant hand, his non-dominant hand, or both hands by comparing sensations with and without haptic feedback.

4) Haptic feedback: In both configurations, the position of the motor is piloted according to the angle formed by the elbow of the avatar.

For now, the rotation of the motor follows this formula :

$$\theta = \frac{\alpha - \alpha_{\text{min}}}{\alpha_{\text{max}} - \alpha_{\text{min}}} \times \frac{M}{M_{\text{max}}} \times 180^\circ$$

where θ is the angle of the motor, α, α_{min} and α_{max} (shown in Figure 8b) are respectively the angle between the direction of the upper and lower arm, the minimum and the maximum of that angle, M is the simulated mass, and M_{max} is the maximum simulated mass.

The reason behind this choice is that the biceps contracts when we are closing our arm, and we want to simulate this sensation. We also want to take into account the impact of the mass we are lifting.

However, this equation is a very simplistic and qualitative approach.

With further experiments, we will be able to integrate a better model for the relation between the angle of the arm in the simulation, the pressure we want to apply, and the angle we need to send to the motor to achieve it.

IV. CONCLUSION AND FUTURE WORKS

We will need to conduct other experiments to have a more precise relation between the rotation of the motor and the pressure exerted on the user's limb.

An other direction to explore is to enable the user to walk in place [10] to control the walking simulation. This would allow a better evaluation of the impact of the prototype in simulations where the user is active, compared to a static equivalent.

For now, no user study has been conducted using these simulations yet. The protocol for this study will follow a few principles : the same participants will experiment the simulation in different configurations, with and without haptic feedbacks, and evaluate several elements on a Likert scale.

For the walking simulation, the haptic device will be attached around the thighs of the user, who will be primarily evaluating the sensation of walking and effort.

For the weight lifting simulation, the haptic feeback will be located on the biceps of the user. In this simulation, we will be mainly focusing on the sensation of effort, as well as the perception of different weights.

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